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Nanodevice fabrication on hydrogenated diamond surface using atomic force microscope

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ABSTRACT

Nanofabrication on a hydrogen-terminated diamond surface is performed using an atomic force microscope (AFM) anodization. Locally insulated areas less than 30 nm are successfully obtained. Side-gated field effect transistors (FETs) are fabricated using the local anodization, and they operate successfully. Single hole transistors composed of one side-gated FET and two tunneling junctions are also fabricated and operate at liquid nitrogen temperature (77 K).

INTRODUCTION

Recently, nanofabrication technology using a scanning probe microscope (SPM) has attracted special interest [1-4]. The fabrication of several nanoscale devices has been reported based on this technique, including nanoscale FETs and single electron transistors (SETs), which have been fabricated by the local anodization of Si, Ti and compound semiconductors [5-8].

Hydrogen termination (H-termination) of diamond surfaces is important because it can stabilize the surface structure. Furthermore, H-terminated diamond is also attractive for electrical applications because it induces p-type surface conduction even in undoped diamond [9-11]. Recently, our group has demonstrated the fabrication and the operation of field-effect transistors (FETs) using a surface conductive layer, and has obtained high transconductance [12,13]. The thickness of this surface conductive layer was estimated to be less than 10 nm, and the surface hole density to be $\sim 10^{13}$ cm^{-2} [11]. On the other hand, an oxygen-terminated (O-terminated) diamond surface is insulating. This means that diamond has an advantage over other semiconductor materials in the fabrication of a surface nanostructure using a SPM-based processing technology.

Since undoped diamond is basically an insulating material, we can conclude that H-terminated diamond has a semiconductor-on-insulator structure. In the case of Si, special techniques such as separation by implanted oxygen (SIMOX) etc. are needed to fabricate the electrically isolated thin conducting layer. In diamond, an electrically isolated surface conductive layer is easily obtained by eliminating the surface H-termination. Recently, local anodization on H-terminated diamond surface was performed using a metal (Au, Rh, etc.) coated conductive atomic force microscope (AFM) cantilever by applying voltage bias to the sample surface [14-17]. Up to the present, local insulation (30-60 nm in line width) has been successfully achieved using AFM. The nm scale separation of H-terminated surface and O-terminated surface will produce new types of nanoscale surface quantum devices such as single charge tunneling devices etc.. In the present study, the fabrication and operation of side-gated diamond metal-insulator-semiconductor FETs (MISFETs) are demonstrated using anodized surface as a gate insulator. Using the locally anodized double tunneling barrier and aforementioned side-gated FET structure, fabrication and operation of single hole transistor is also demonstrated.

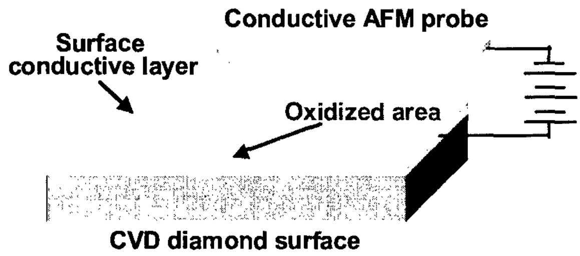


Figure 1. Schematic of AFM nanofabrication on the hydrogen-terminated diamond film surface.

EXPERIMENTAL

For sample preparation, microwave-plasma-assisted chemical vapor deposition (CVD) with a CH_4/H_2 gaseous source is used. Undoped homoepitaxial diamond thin films are fabricated on high-pressure, high-temperature (HPHT) synthetic (001) diamond single-crystal substrates. After the deposition, undoped diamond films are exposed to hydrogen plasma to perform hydrogen termination. A scanning probe microscope system (Seiko Instruments: SPI3800N) and Au or W_2C-coated conductive AFM probes made of Si are used to perform surface anodization (figure 1). In the device fabrication process, electron beam lithography is used for the ohmic gold electrode fabrication, and channel isolation was carried out by Ar ion irradiation before the AFM anodization.

RESULTS AND DISCUSSION

Figure 2(a) shows an AFM topographic image of the modified diamond surface after line scanning under 5 V sample bias applied in air. In this case, surface protrusion is observed in the

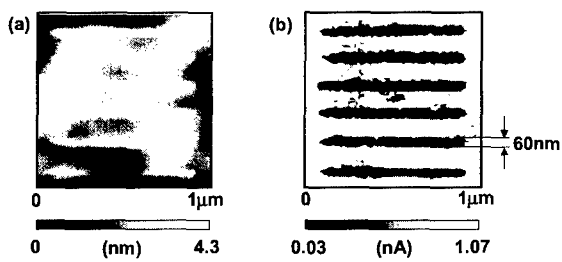


Figure 2. (a) Topographic images of diamond film surface after AFM modification (bias: 5 V, scan speed: 100 nm/s), (b) Current image under the application of 2 V sample bias

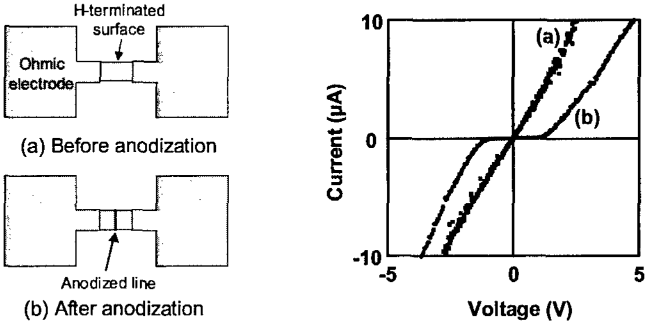


Figure 3. Current-voltage characteristics of H-terminated diamond suraface across the anodized region.

AFM-anodized area of 60 nm line width. In figure 2(b), the current image simultaneously obtained with topographic measurement is shown. During the current measurement, 2 V bias which is below the anodizing voltage is applied to the sample surface. In this figure, one can see that local insulation is successfully achieved. The insulated line width is about 60 nm. Current-voltage characteristics are measured across the anodized line at room temperature. Before the anodization, the current-voltage relation is almost ohmic (figure 3(a)). After making the anodized line (line width 60 nm), the current is suppressed at low -1 V $<V<1$ V (figure 3(b)). At a higher bias range ($|V|>1$ V), the current starts flowing through the insulated line by Fowler-Nordheim (F-N) tunneling and/or thermionic emission. Consequently, one can say that anodized region can be used as the potential barrier to the hole existing in surface conductive layer.

Figure 4 shows the schematic and the I_{DS}-V_{DS} characteristics of side-gated diamond FET fabricated by AFM local anodization. Source-drain channel is separated from the gate surface conductive area by anodized region. Current saturation is observed in the statistic characteristics,

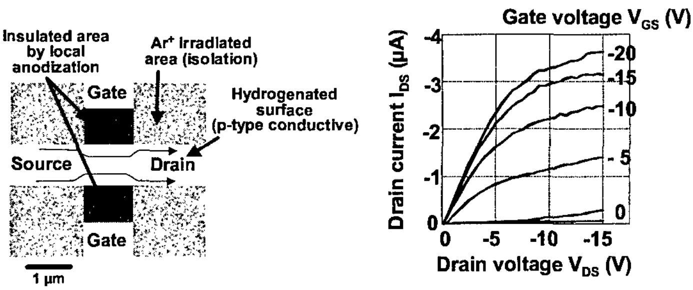
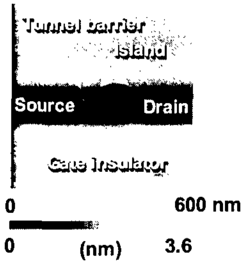


Figure 4. Schematic and statistic characteristics of side-gated FET (gate length: 1 μm) using local anodization by AFM.



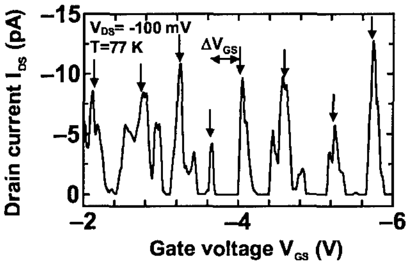


Figure 5. AFM image and V_{GS}-I_{DS} characteristic of diamond single hole transistor fabricated by AFM nano anodization.

and channel current is well modified by the field effect. Threshold gate voltage is 0 V, though slight short channel effect occurs at higher drain bias. Channel is depleted even at 0 V gate bias. This is attributed to the surface carrier trap existing at the anodized region.

Based on these results, single hole transistor is fabricated using AFM-anodized area as a gate insulator and tunneling barriers. Figure 5 shows the AFM image and measured characteristic of the fabricated single hole transistor. A conductive island (100 X 120 nm^2) is separated from source and drain by the anodized tunneling barriers (40 nm in width). In the V_{GS}-I_{DS} characteristic under −100 mV drain bias condition measured at liquid nitrogen temperature (77 K), clear current oscillation is observed. This oscillation can be attributed to the coulomb blockade oscillation. However, the area of the island deduced from the period of this oscillation (ΔV_{GS} ~0.4 V) is in the order of nm. This value is smaller than aforementioned island area. If we consider the carrier depletion in the island, many smaller conductive regions appears in the isolated island. Subpeaks besides the main oscillation peaks in the current oscillation also suggests this multiple island model.

CONCLUSIONS

Local insulation on H-terminated diamond surface conductive layer was performed using AFM-based nano anodization. Based on this technology, the operation of 1 μm side-gated diamond MISFETs is performed using anodized surface as a gate insulator. This FET operates in enhanced mode and field-effect modulation of channel current is successfully achieved by the side-gated MIS structure. Using the locally anodized double tunneling barrier and side-gated FET structure, fabrication and operation of single hole transistors are also demonstrated for the first time. In the V_{GS}-I_{DS} characteristic, coulomb blockade oscillation is observed even at liquid nitrogen temperature (77 K).

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